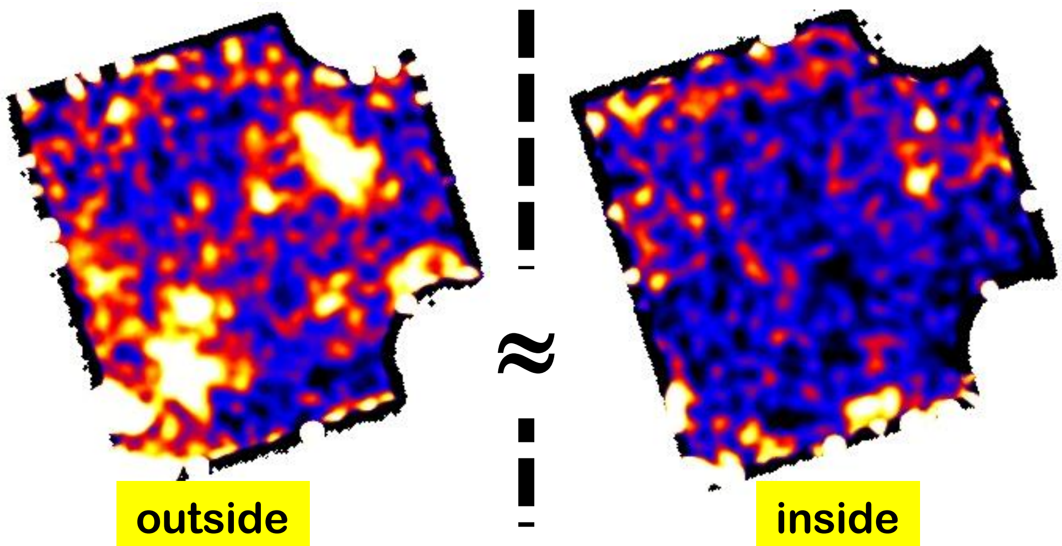
The Fermi Bubbles: Theory and Observations,
2013, Apr.11-12

X-ray Observations of the Fermi Bubble



Fermi Bubble edge

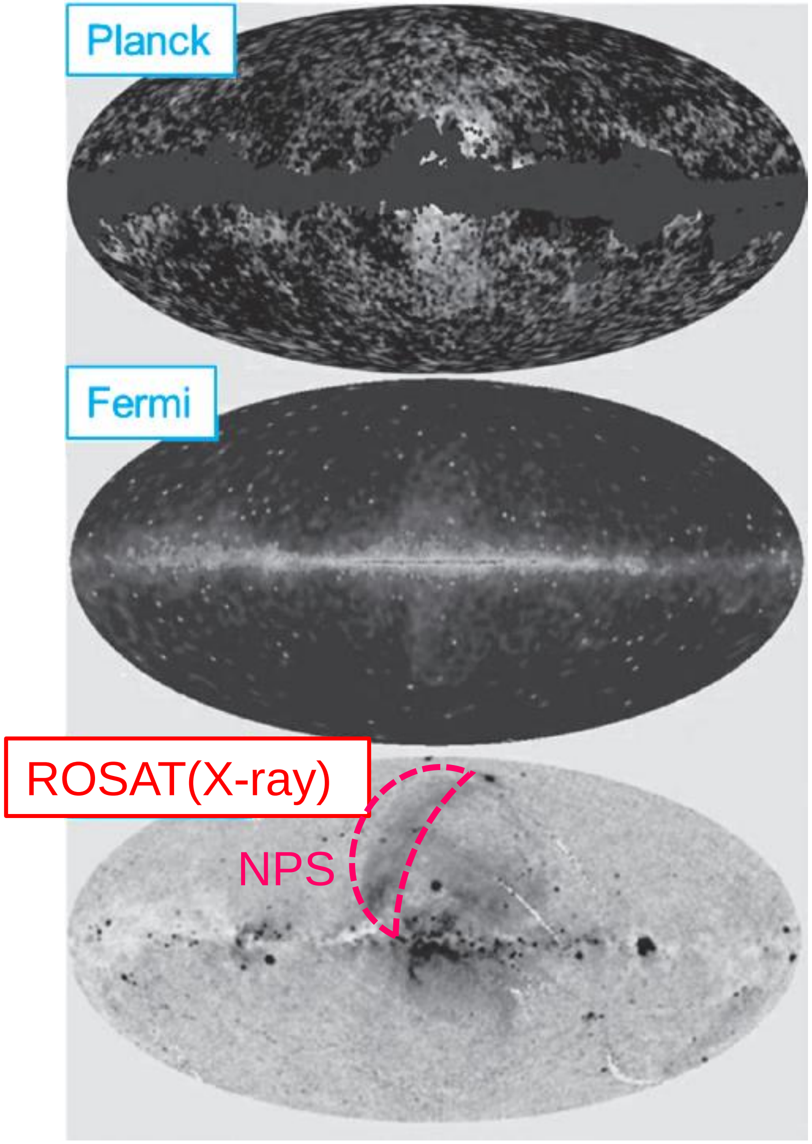
Jun KATAOKA (Waseda Univ.)

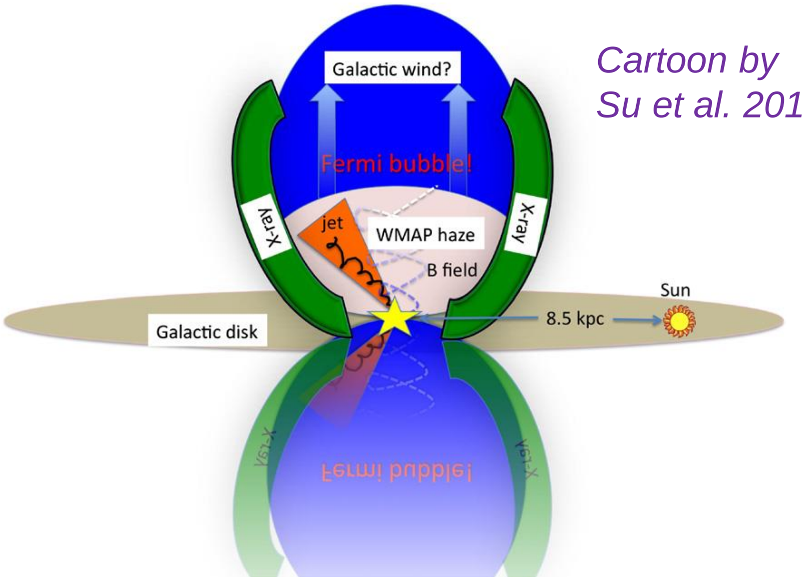
Special thanks to T.Totani (Univ. of Tokyo), M.Tahara, Y.Takahashi, Y.Takeuchi, T.Nakamori (Waseda Univ.), H.Tsunemi (Osaka Univ.), M.Kimura, Y. Takei, L.Stawarz (ISAS/JAXA)

Outline

- Introduction – all-sky view in X-ray
  - Fermi, Planch and ROSAT
  - New comer : MAXI SSC (1.7 – 4.0 keV)
- X-ray Observations of the Galactic Halo
  - Isotropic emission
  - Distribution of EM and kT
- X-ray observations of NPS
  - Close or far away?
  - Suzaku observation across NPS edge
- Summary and Discussion
  - Interpretation of results
  - Other evidence

X-ray Envelop of the Bubble





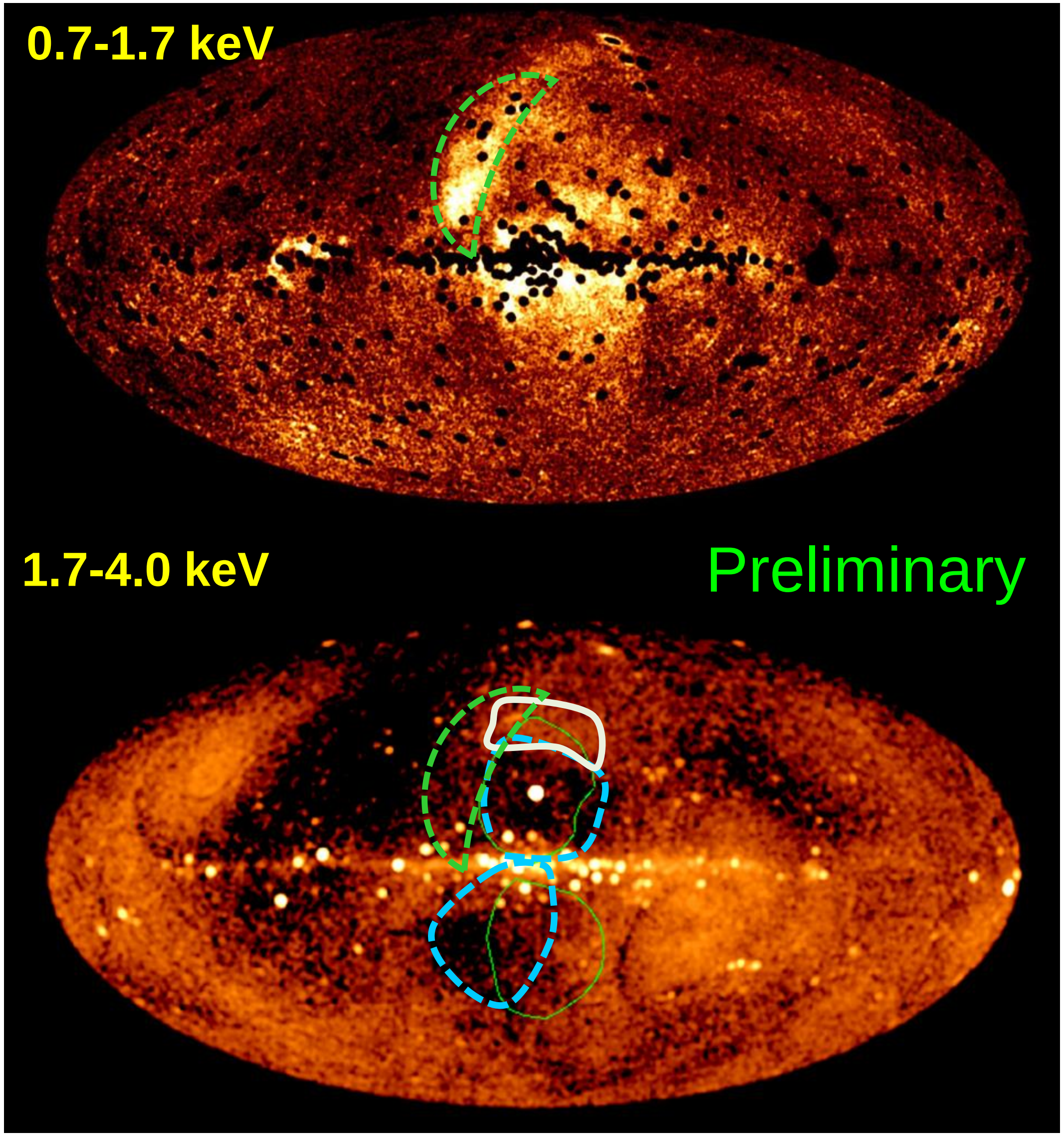
Cartoon by Su et al. 2010

- Bubbles are spatially correlated with the *WMAP* haze, and also the edges of the bubbles line up with features (**NPS**) in the *ROSAT* map at 1.5 keV
- The model assuming the past activity of GC makes such X-ray feature is based largely on morphological arguments, but being more common these days

Sofue et al, 2000; Bland-Hawthorn and Cohen 2003

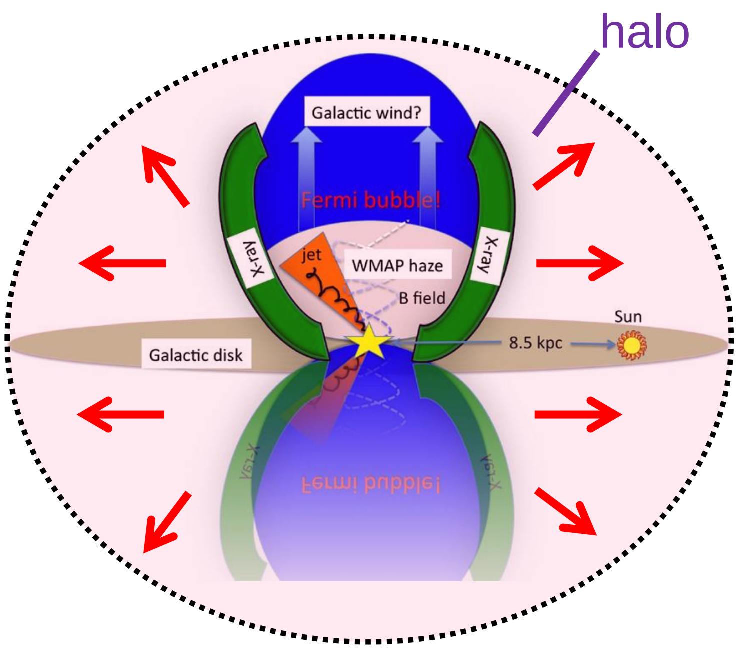
More will come with MAXI

Kimura et al. 2012; MAXI-SSC team in prep



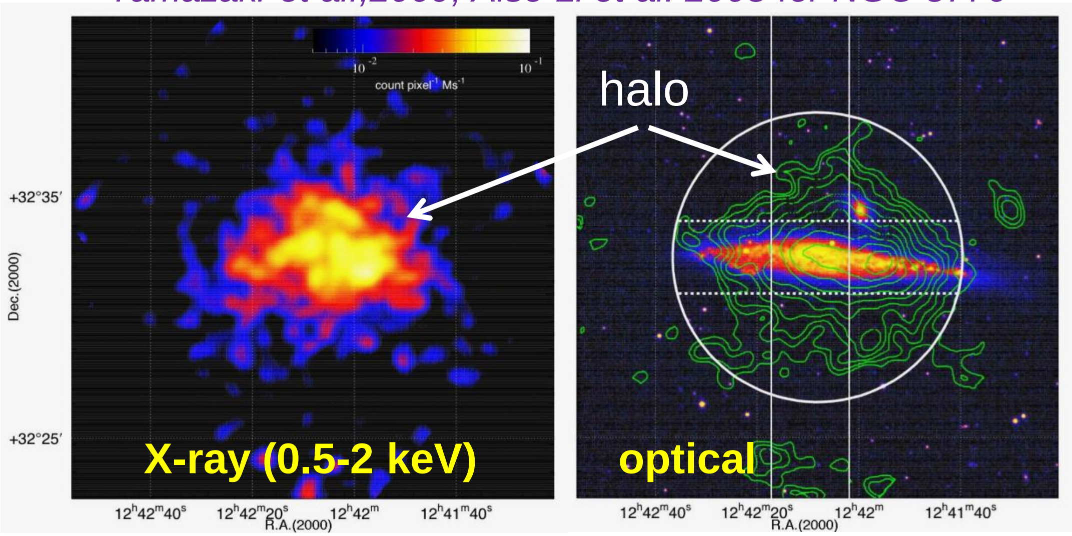
- Recent all-sky X-ray monitoring w/ *MAXI*-SSC confirmed global structure already found w/ *ROSAT* below 1.7 keV
- Above 1.7 keV, however, X-ray features seems to have changed largely, such as “void” structures both in the north and south, lack of NPS, but enhanced X-ray emission at the top of N-bubble (but still preliminary,,,)
- There still remains a big discovery space in the X-ray data, especially above 2 keV, currently being prepared/provided by *MAXI*-SSC

X-ray Halo and Bubble



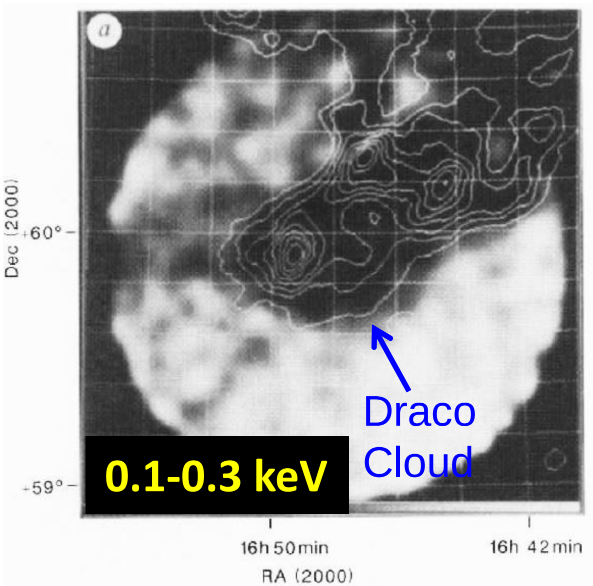
NGC4631 (edge-on spiral galaxy)

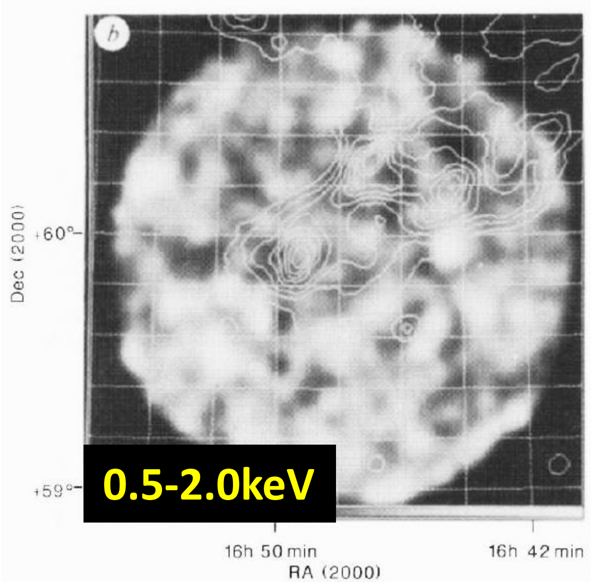
Yamazaki et al.,2009; Also Li et al. 2008 for NGC 5776



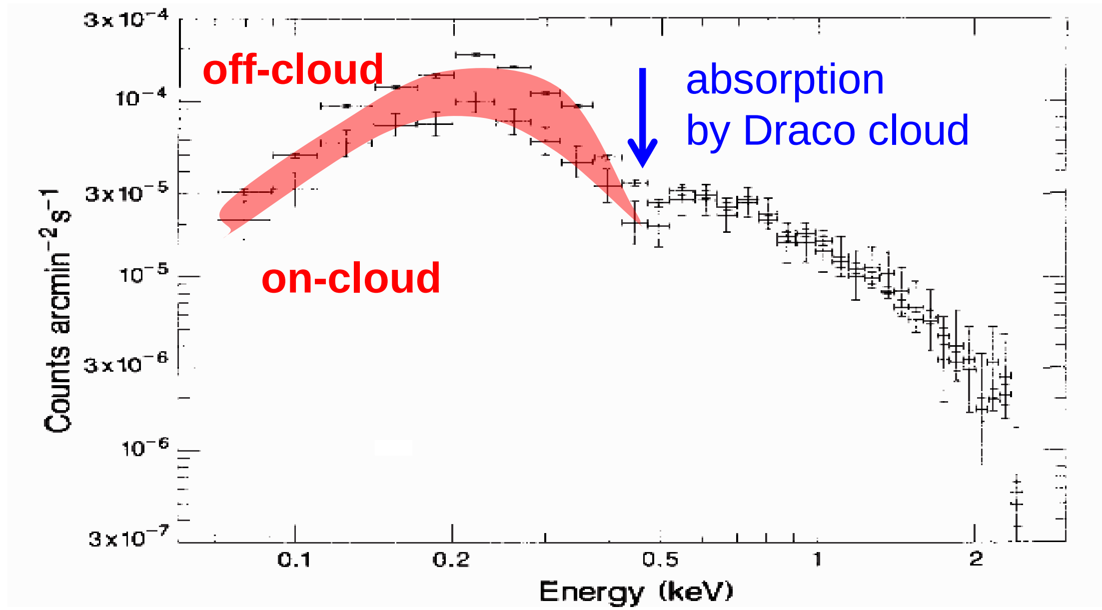
- The bubbles might be fast expanding shock and finally expand freely into the Galactic halo, thus contaminating the ISM with entrained hot gas
- Although the nature and origin of halo is still not well known, nearby spiral galaxies often exhibit X-ray halo extending out to about ~10 kpc from the disk, with typical temperature of kT ~ 0.1 - 0.6 keV
- ***if*** the giant X-ray structure like NPS is associated with the bubble, we must *a priori* consider observational properties of *halo in our Galaxy*

Evidence of halo in our Galaxy





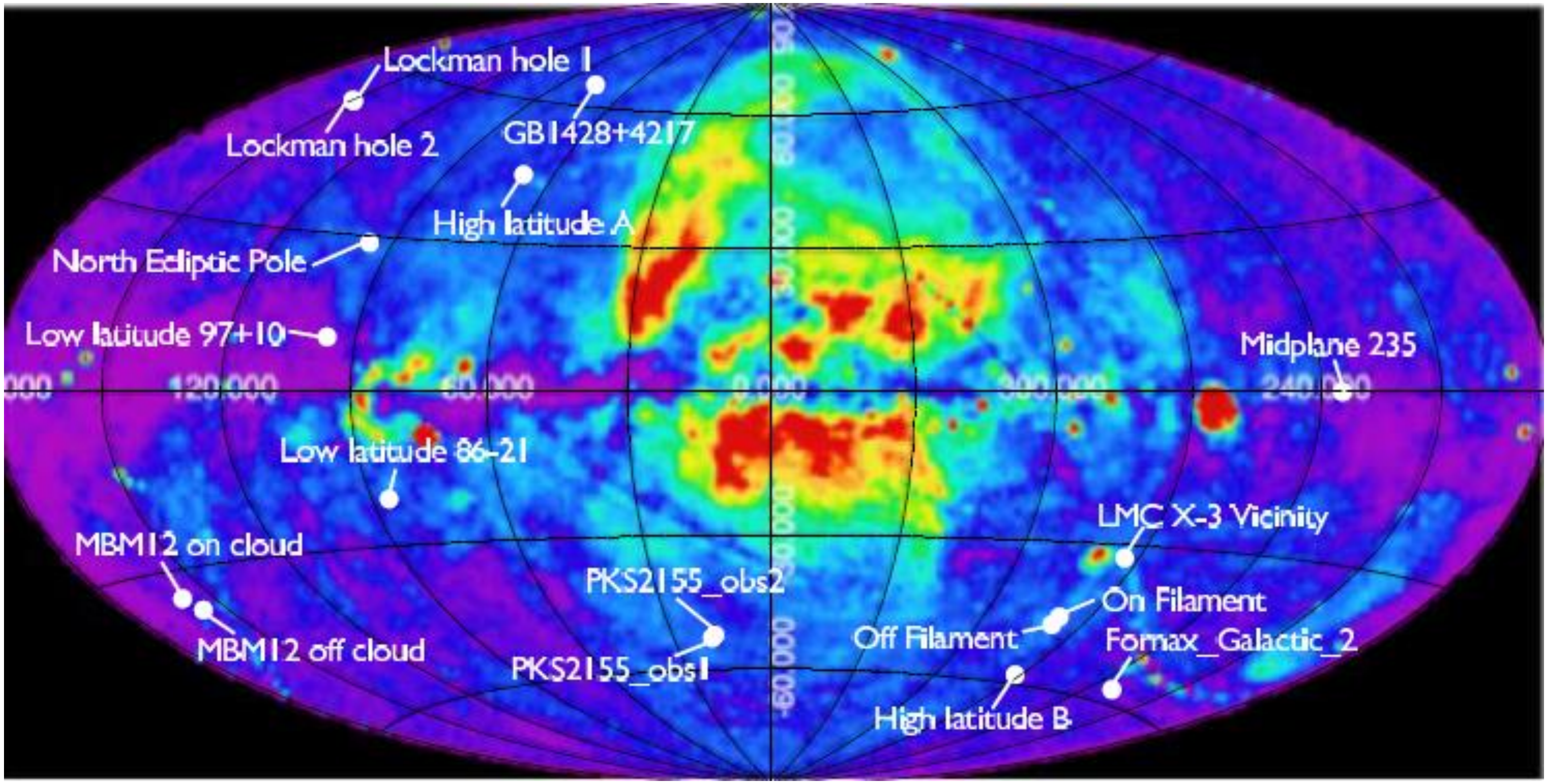
Burrows & Mendenhall 1991



- Using the *ROSAT*, shadowing of the soft X-ray background was clearly detected in the 0.25 keV band by unusual interstellar cloud in Draco
- The Draco cloud is at the high galactic latitude of b= 39°, and at d > 300 pc from the Sun
- Results of X-ray shadowing suggest the first direct evidence for a kT ~0.1 keV halo of gas

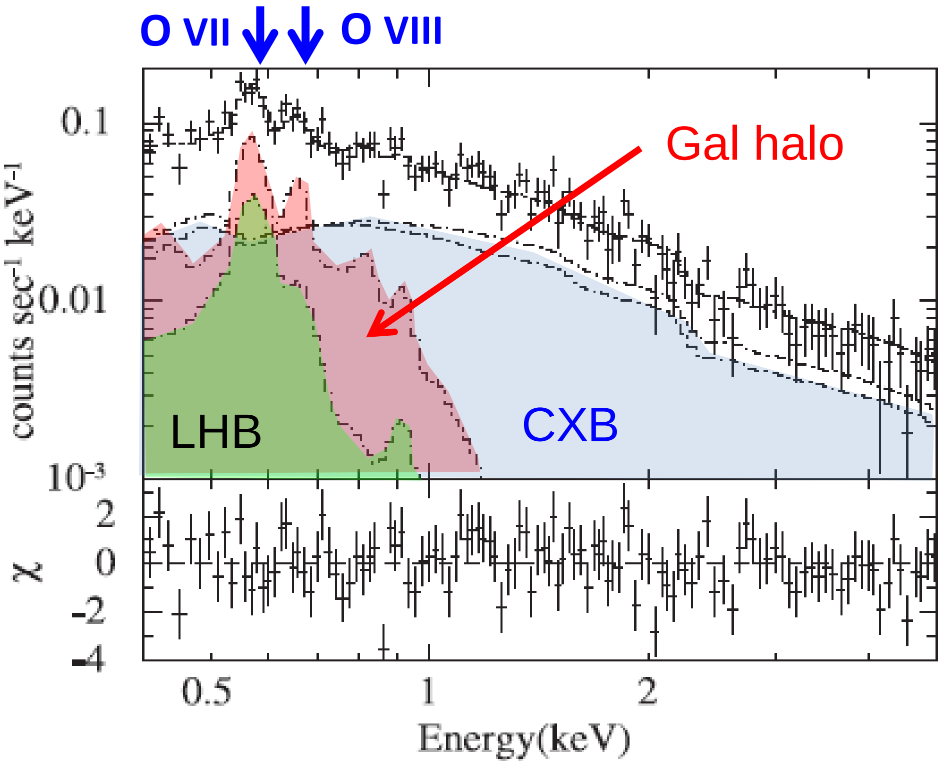
X-ray mapping of the halo

Yoshino et al. 2009

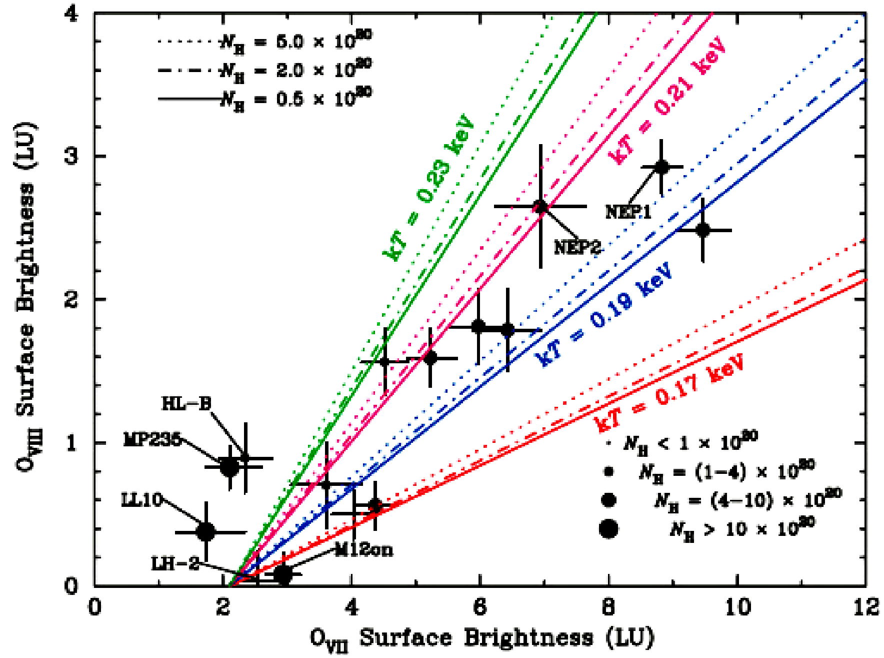


- Uniform analysis of the soft diffuse X-ray emission of 12+2 fields observed w/ Suzaku, where $65^o < l < 295^o$ to avoid contribution from the bright structures like NPS and bulge near the GC
- Thanks to good energy response function of the CCD camera OVII and OVIII emission are clearly resolved, that helps a lot to determine plasma temperature in the halo

Halo kT measurement by Suzaku

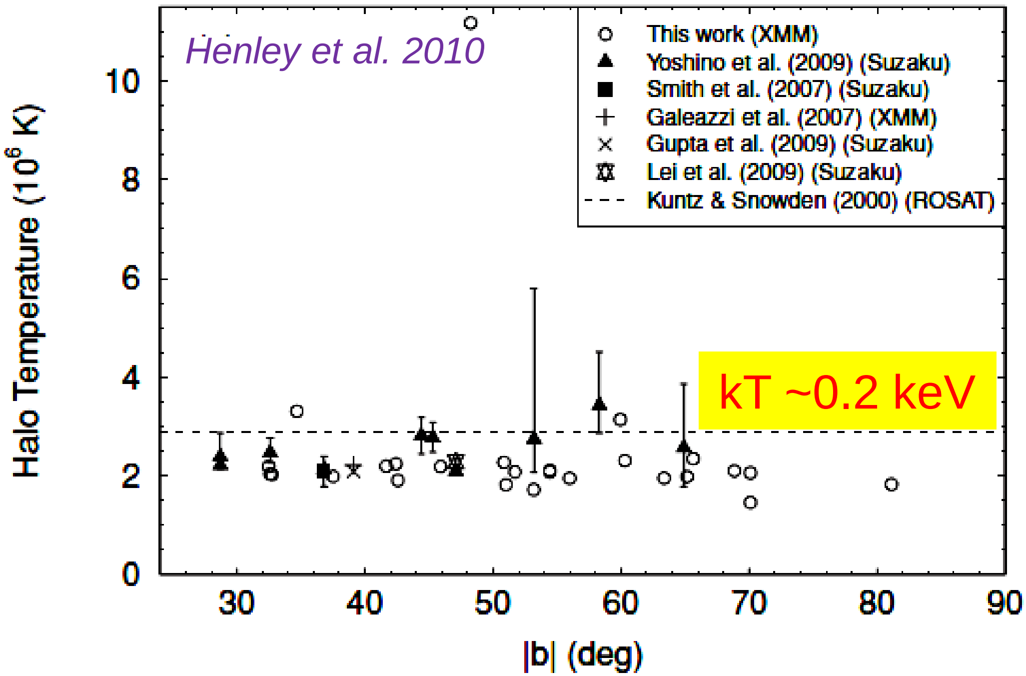


Yoshino et al. 2009

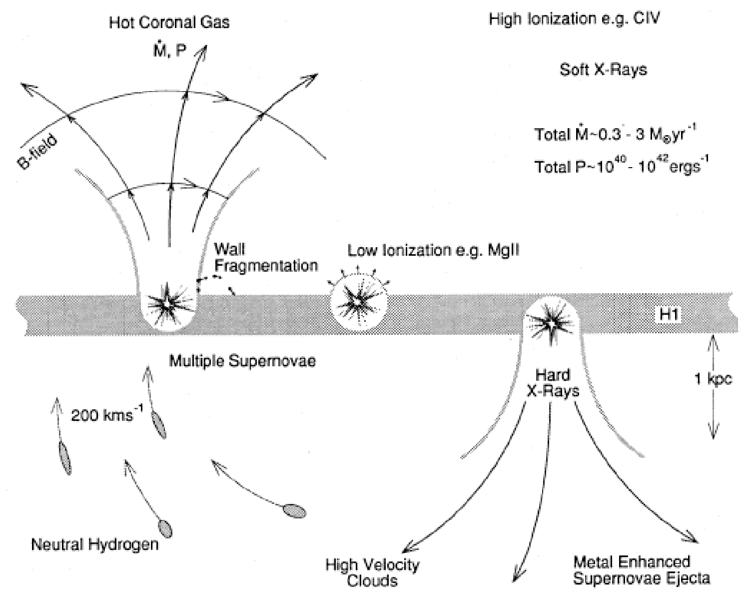


- Basically, the spectra of all the field is well represented by
  (1) $kT \sim$ 0.1 keV w/o Galactic absorption : LHB + SWCX
  (2) $kT \sim$ 0.2 keV w/ full Galactic absorption : Galactic halo
  (3) Power law w/ $\Gamma \sim 1.4$: CXB
- A tight correlation between O VII and O VIII brightness suggests that kT averaged over different line-of-sight show a narrow distribution of ~ 0.2 keV (offset of O VII due to LHB + SWCX)

Halo kT measurement by XMM



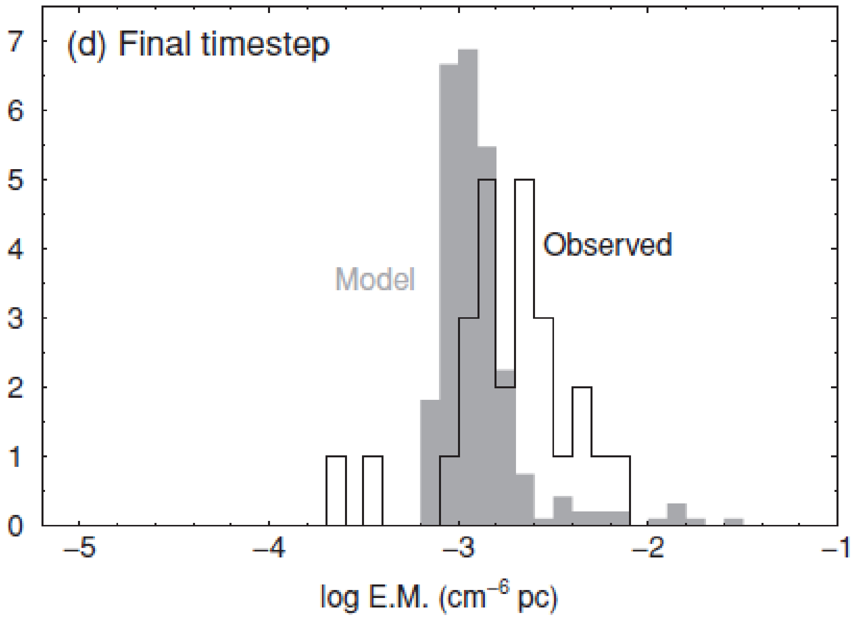
Norman & Ikeuchi 1989

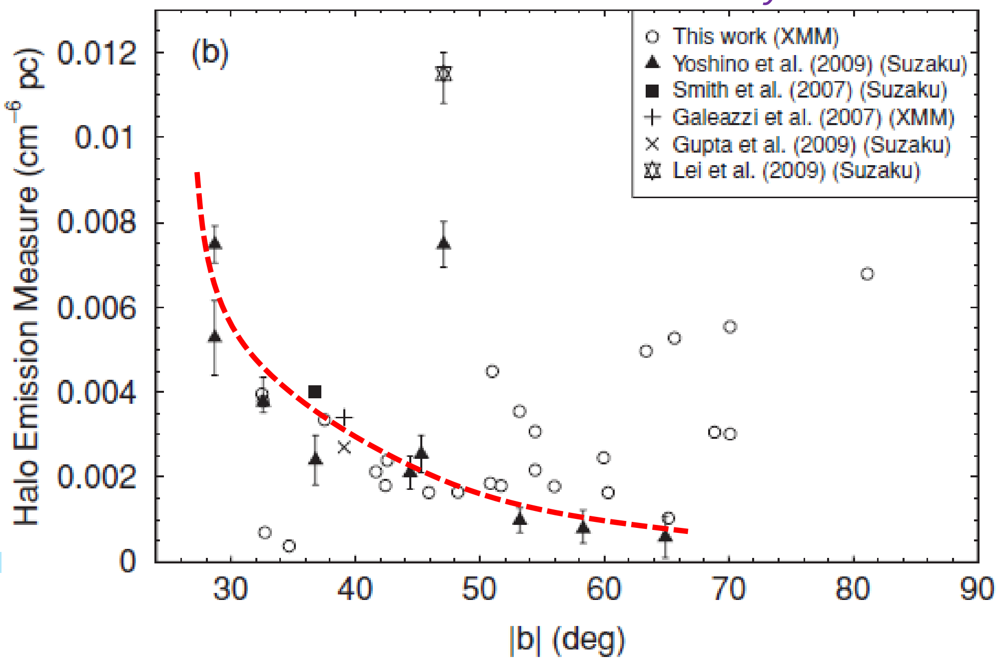


- Similar study using 26 high latitude XMM observations of the soft X-ray background between 120º < l < 240º also suggests that observed halo temperature is fairly constant across the sky, **0.16 keV < *kT* < 0.21 keV**
- They compared the observed X-ray properties of the halo with the three physical models for the origin of the hot gas: (1) a disk galaxy formation model (2) a model in which the halo is heated by extraplanar SNe, and (3) a fountain of hot ISM gas driven into the halo by disk SNe, which they argue (3) is most likely

EM of the "Galactic Halo"

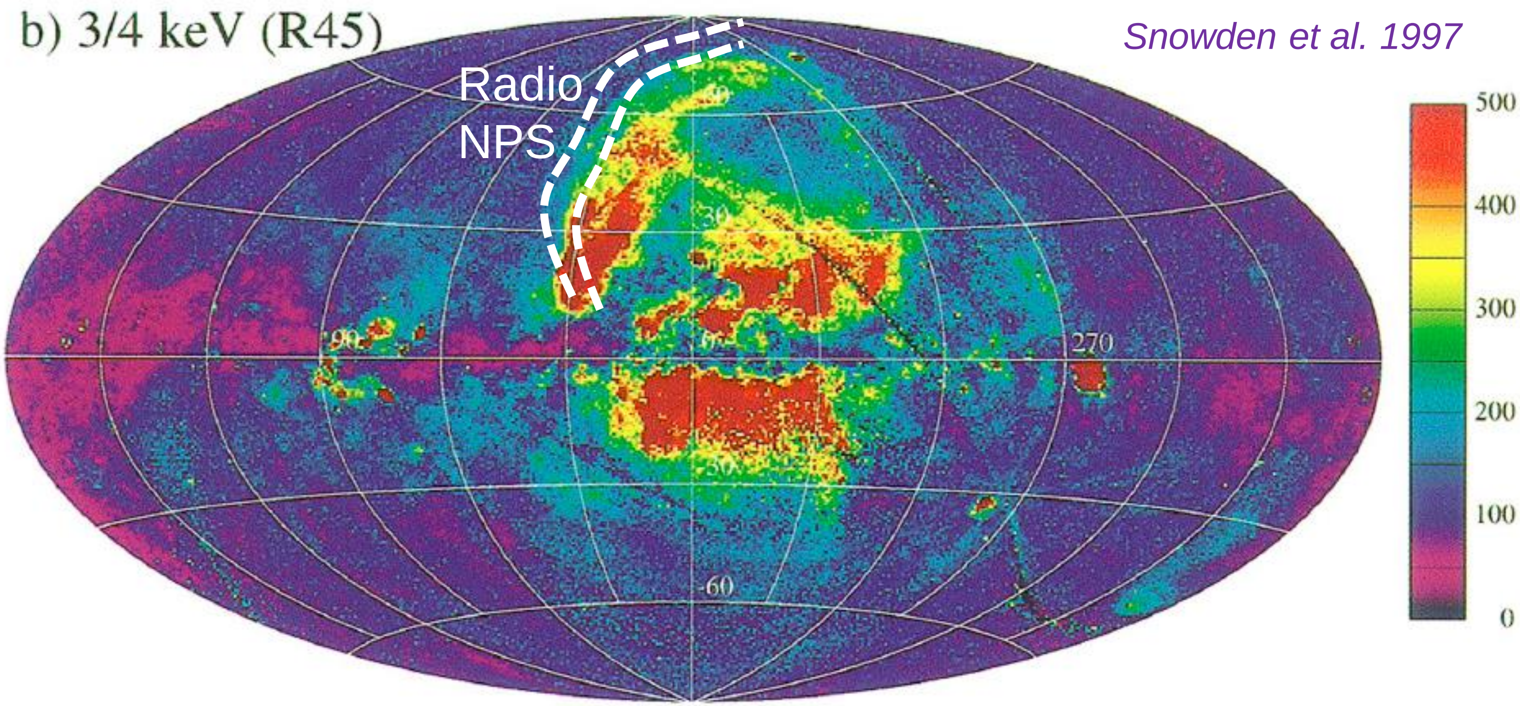
Henley et al. 2010





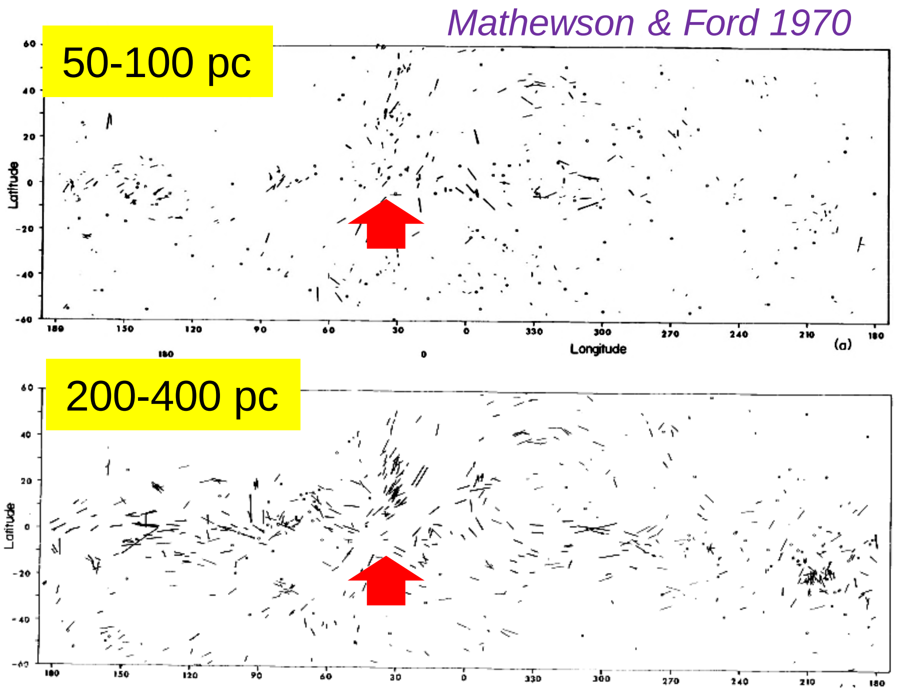
- In contrast to uniform *kT* of the halo, the halo emission measure (EM) varies by an order of magnitude (EM = $0.5 \times 10^{-3} \sim 6 \times 10^{-3}$ cm^{-6} pc).
- Model (3) of an SN-driven ISM, including the flow of hot gas from the disk into the halo in a galactic fountain, gives good agreement with the observed 0.4–2.0 keV surface brightness
- This model, however, over-predicts the halo X-ray temperature by a factor of ~2, but there are a several possible explanations for this discrepancy.

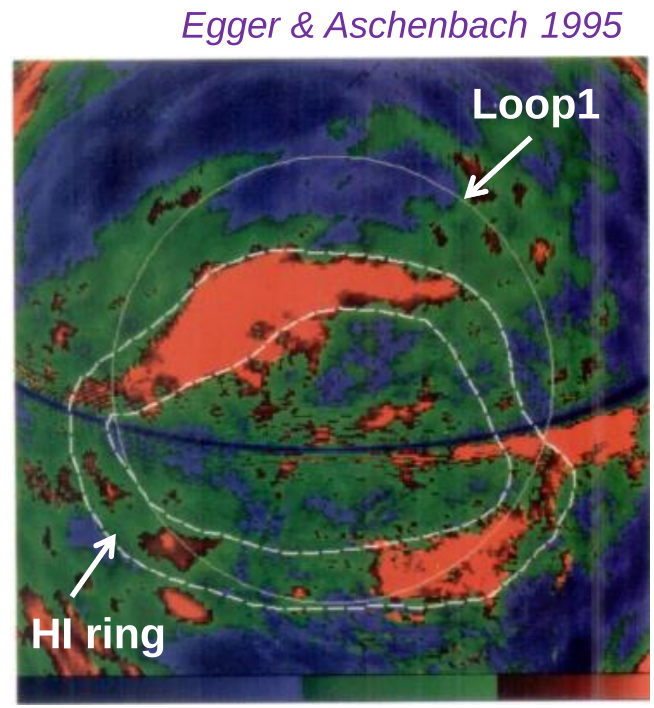
North Polar Spur : “close” or “far away” ?



- NPS is a region of enhanced soft X-ray and radio emission projected above the plane of the Galaxy, associated with the bright radio continuum Loop I (but there is some offset seen!)
- Two different scenarios have been argued for the origin on NPS:
  [A] local nearby SNR *(Egger 1995; Willingale et al. 2003; Milller et al. 2007 ++)*
  [B] huge structure associated with mass outflow from GC
  (Sofue 2000; Totani 2006; Su et al. 2010 ++)

NPS – [A] nearby SNR?



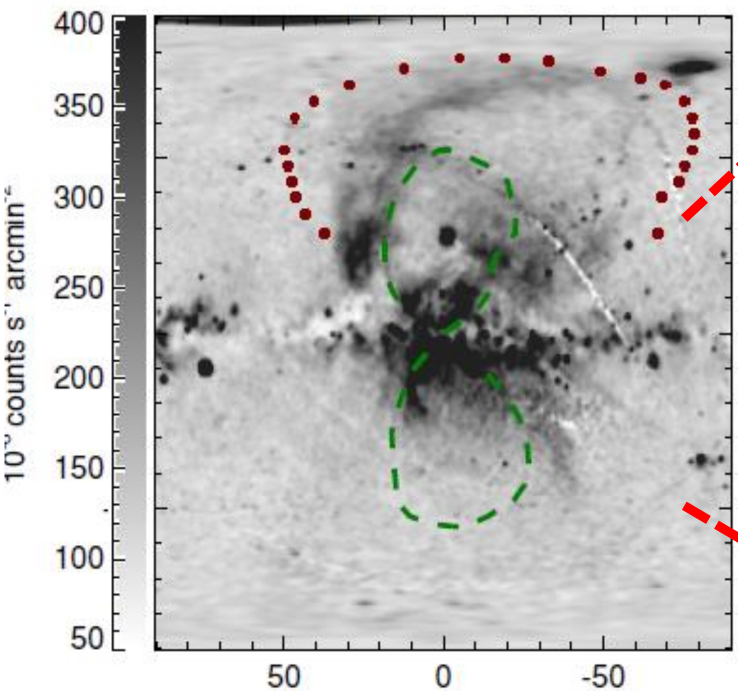


- An interstellar polarization feature at distance of ~100 pc which clearly follows much of the N- and E- parts of Loop I, including the NPS, with the expected polarization orientation *(Mathewson & Ford 1970)*
- In addition, the H I features seen nearby (~70pc) appear to be due to an interaction of Loop I with the Local Bubble, although somewhat speculative *(Egger & Aschenbach 1995).*

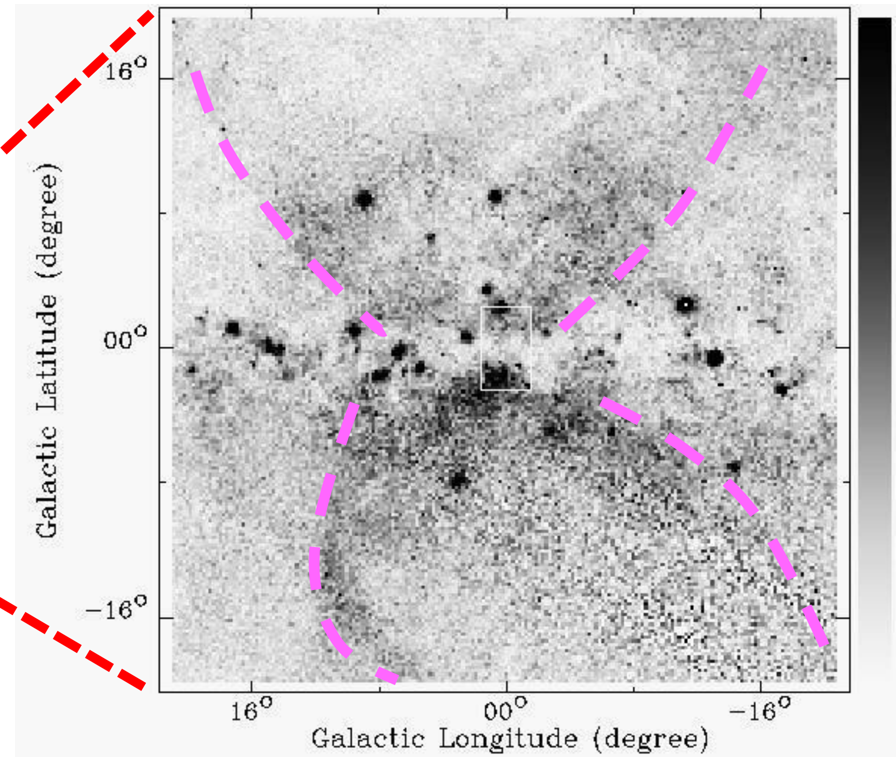
These results favor the local NPS scenario

NPS – [B] GC origin?

Su et al. 2010



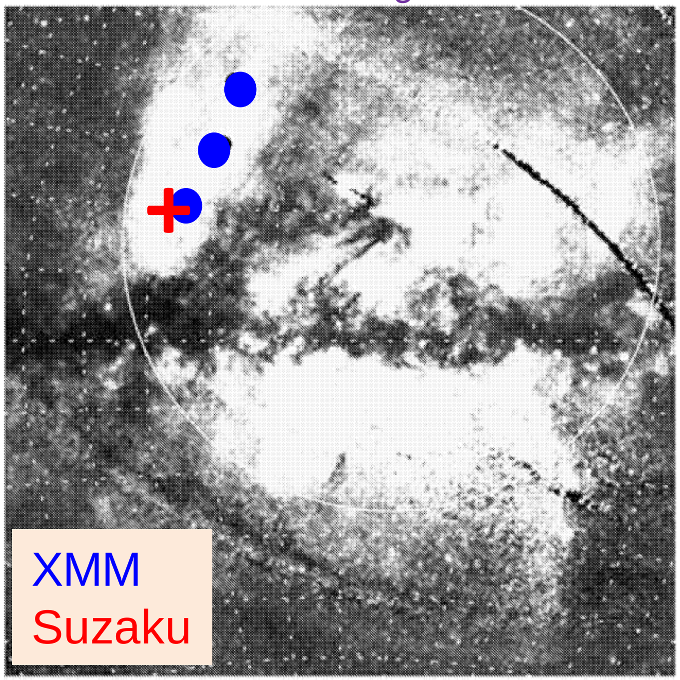
Wang et al. 2002



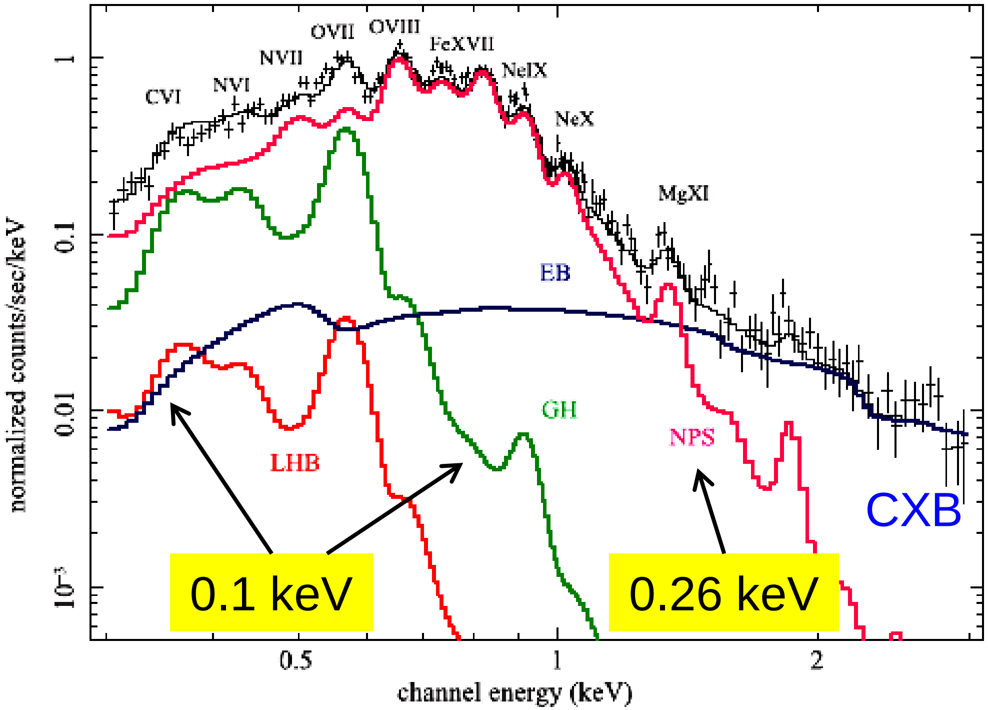
- Under the “GC model”, the NPS is the remnant of a starburst or explosion near the GC ~15 Myr ago and is at a distance of several kpc. But this scenario is based largely on morphological arguments
- However, the *ROSAT* 1.5 keV image presented by Wang (2002) clearly shows the hourglass geometry characteristic of a bipolar flow, even in the South of GC with angular scale of more than ~20^{o} !

NPS in X-ray : Suzaku & XMM

Willingale et al. 2003



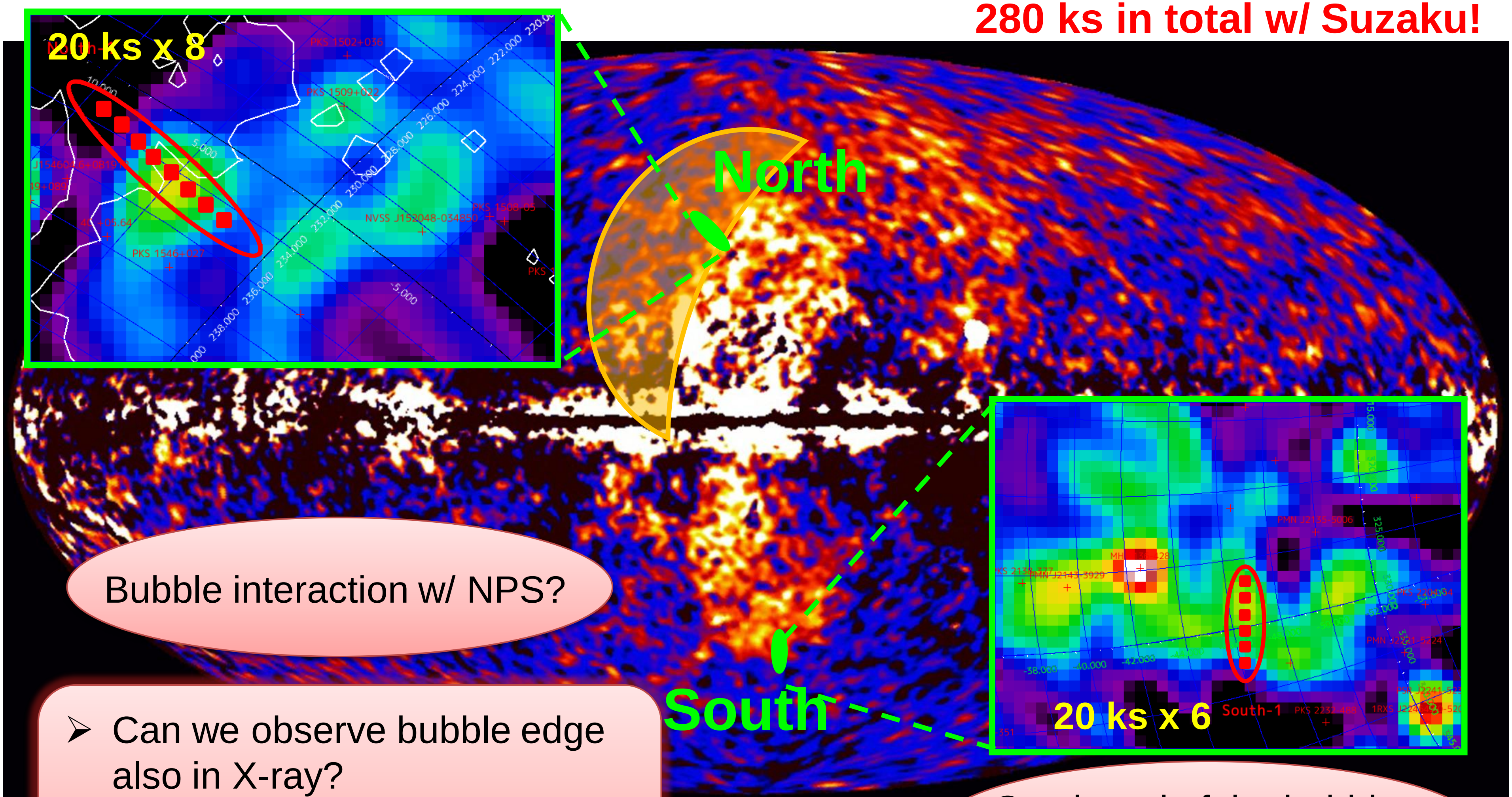
Miller et al. 2007



- Three distinct Galactic plasma components are identified; a cool local hot bubble (and assumed "cool" hot Galactic halo) of $kT \sim 0.1$ keV and a hotter component of $kT \sim 0.26$ keV associated w/ NPS itself, with depleted C, O, Ne, Mg, and Fe abundances of less than 0.5 solar, but an enhanced N abundance
- *XMM* spectra at different Galactic latitude of b = 20, 25, 30^{o}, was quite similar except for normalization (or EM) of $kT \sim 0.26$ keV component

Suzaku Observation in 2012

280 ks in total w/ Suzaku!



Bubble interaction w/ NPS?

- Can we observe bubble edge also in X-ray?
- Non-thermal or thermal emission, or both ???

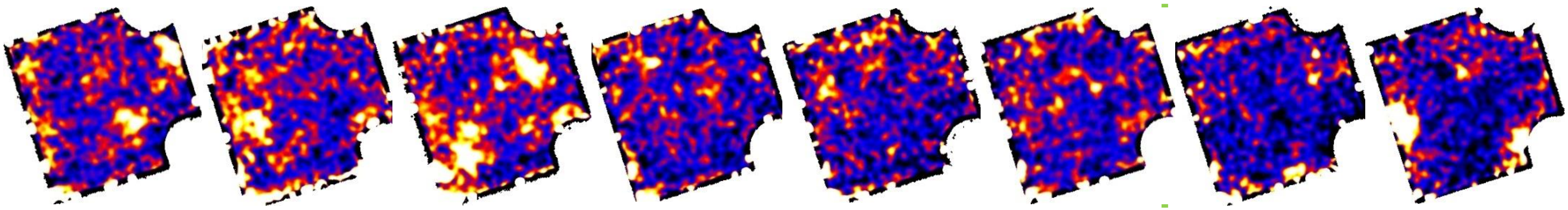
South end of the bubble – like jet termination in AGN?

Overview : 0.4-10 keV image

FB North

out-side

in-side

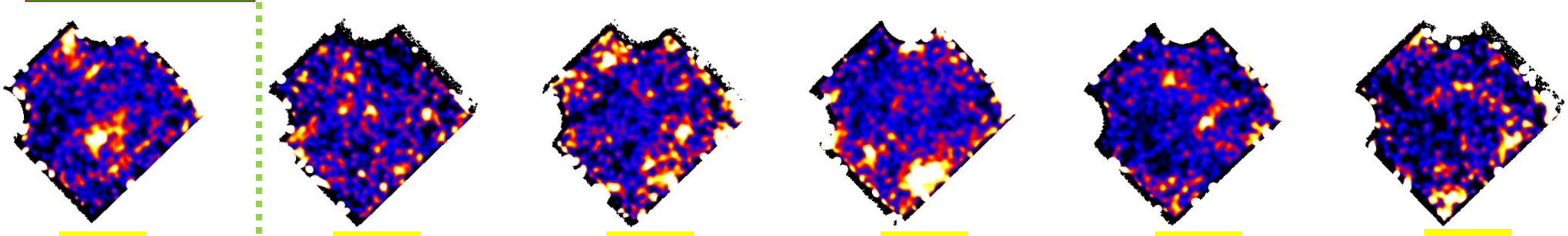


N1 N2 N3 N4 N5 N6 N7 N8

Toward the GC

Bubble edge

FB South



S1 S2 S3 S4 S5 S6

out-side

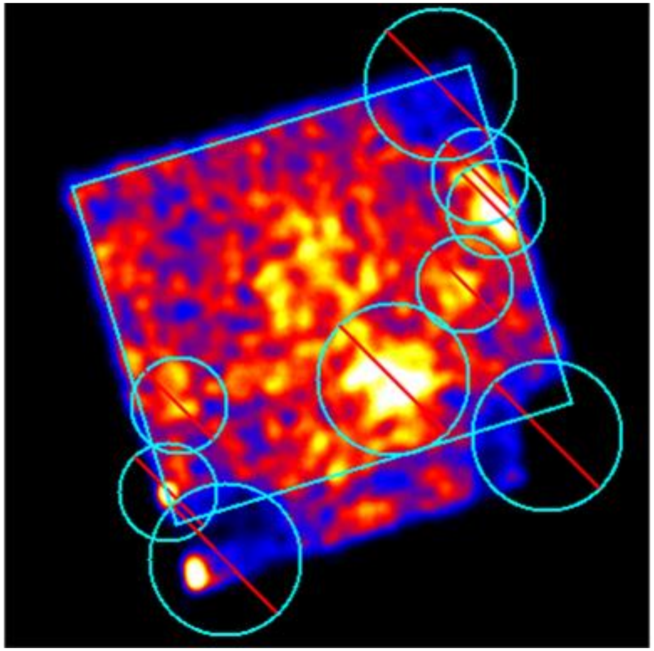
in-side

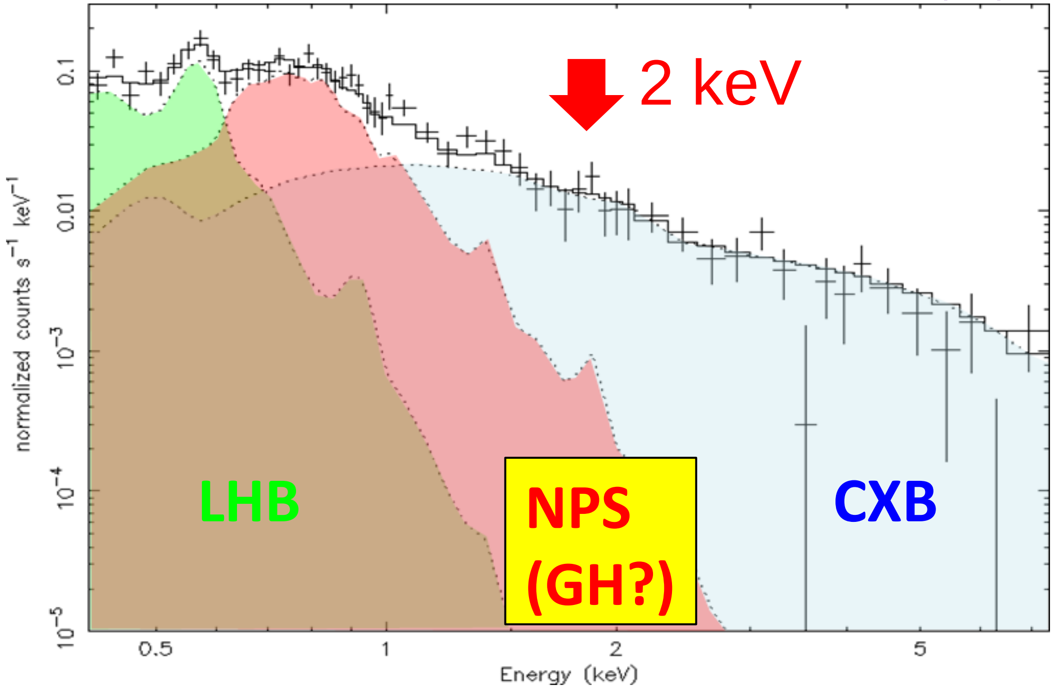
Toward the GC

Bubble edge

Suzaku: Spectrum (Diffuse Emission)

Kataoka et al. 2013, in prep

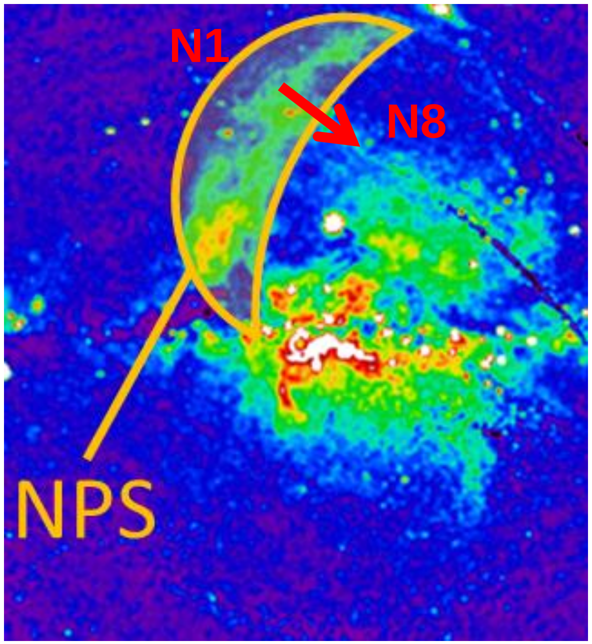


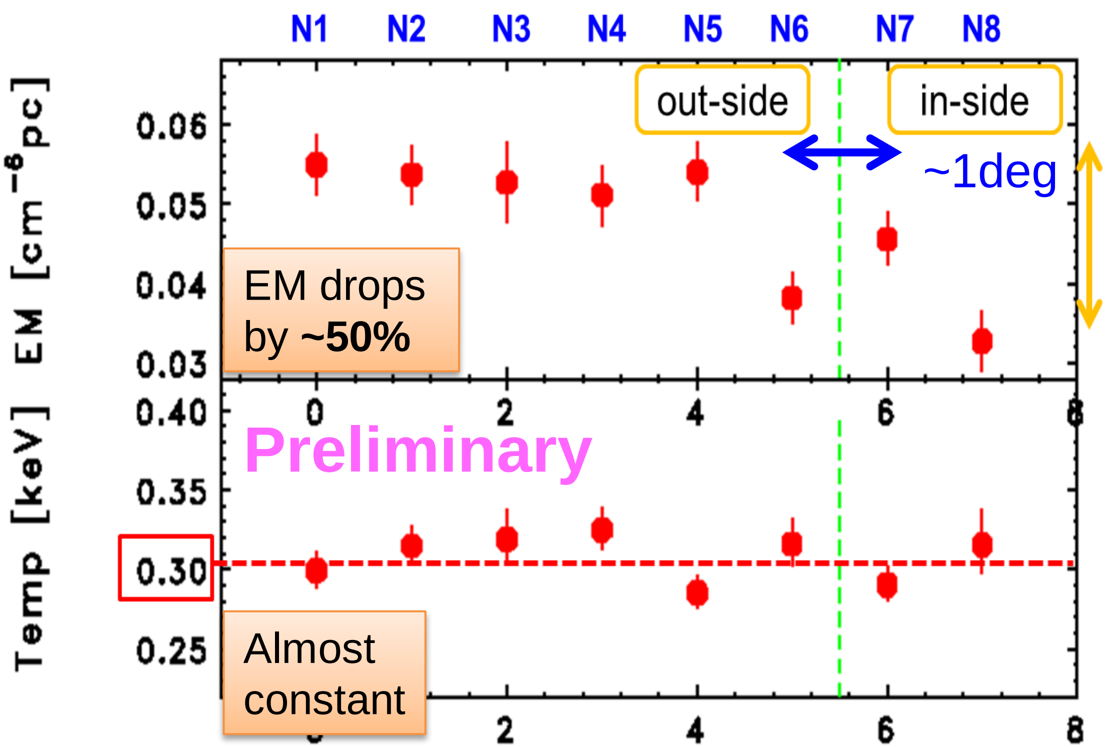


- In the analysis, we consider "diffuse X-ray emission" only, that is the remaining component after removing known/unknown point sources in the FOV, detected at $>3\sigma$ confidence level (analysis of point sources will come later!)
- X-ray spectrum of the bubble edge is well represented again by three distinct Galactic plasma components, but *non-thermal diffuse X-ray associated with the Fermi Bubble was not detected!*

EM and kT across the bubble edge

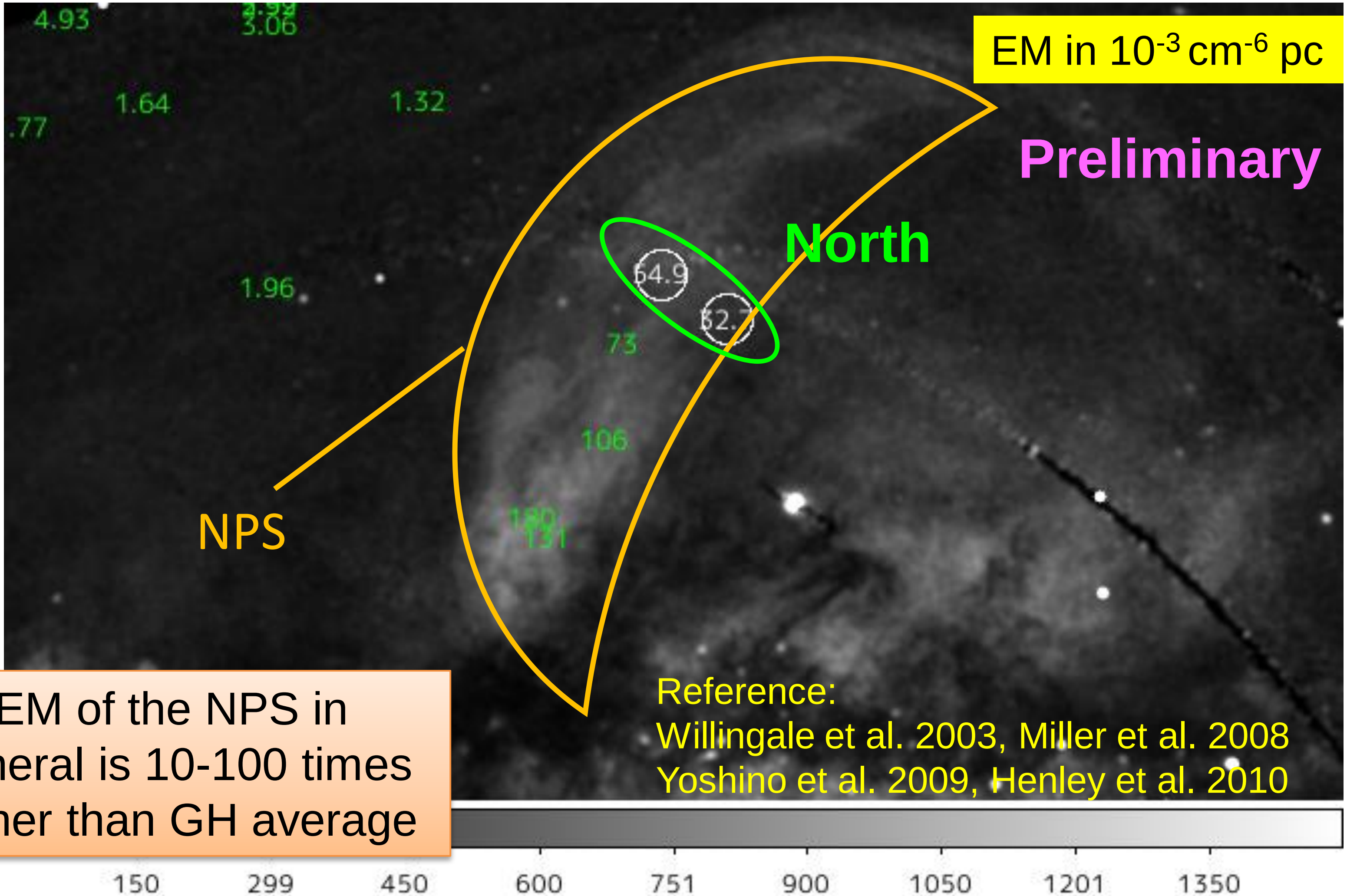
Kataoka et al. 2013, in prep





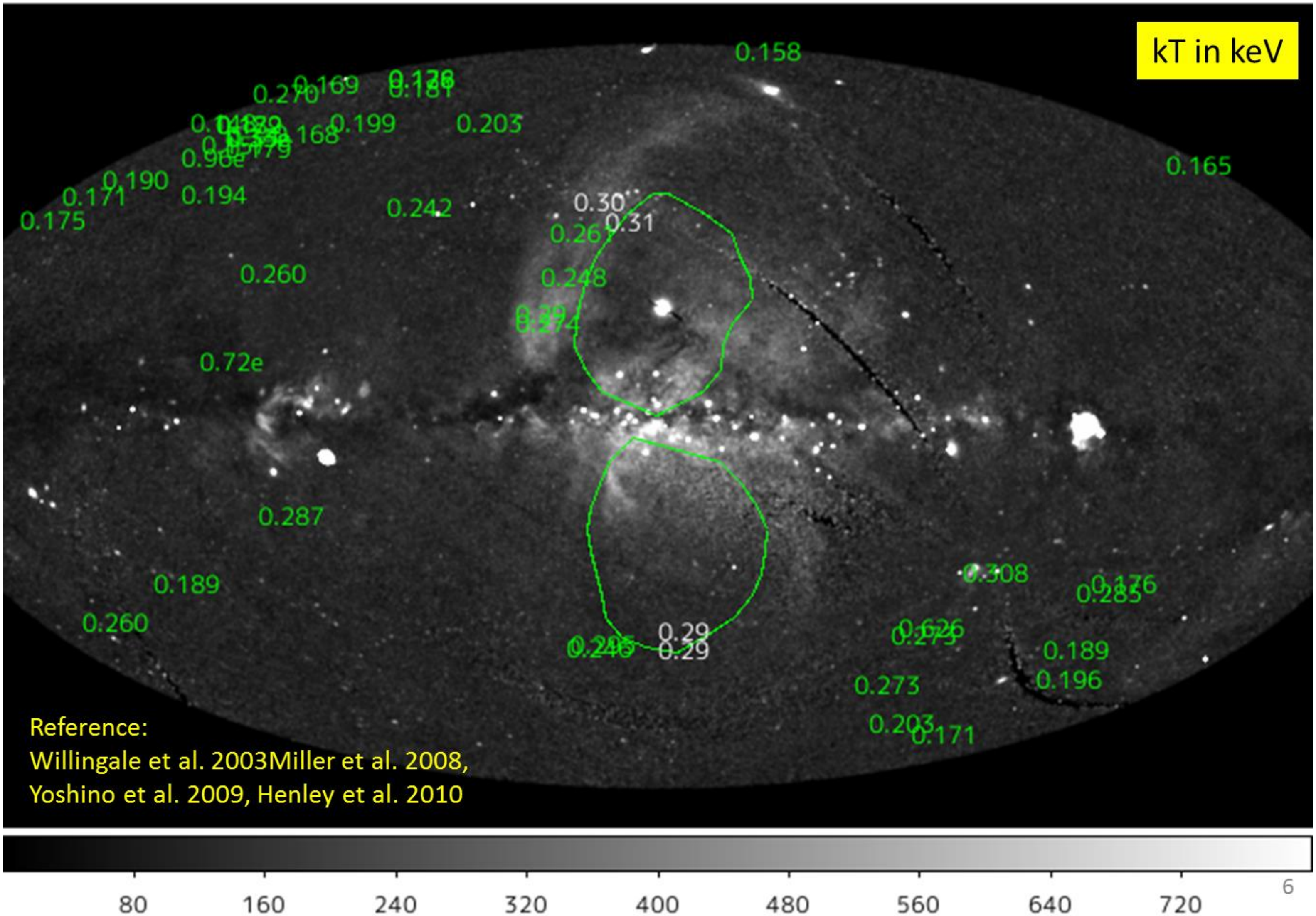
- Interestingly, EM drops about 50 % near the expected bubble edge, while the temperature of NPS/GH component stays almost constant at $kT \sim 0.3$ keV, a bit hotter than the brightest part of the NPS at low Galactic latitude (such clear jump couldn't be seen in the South bubble edge)
- Assuming scale length of L = 1kpc, n_e jumps ~20 % from $7.5\text{x}10^{-3}$ cm^{-3} to $6.0\text{x}10^{-3}$ cm^{-3}, as EM $\propto n_e^2$

EM distribution near the N-edge

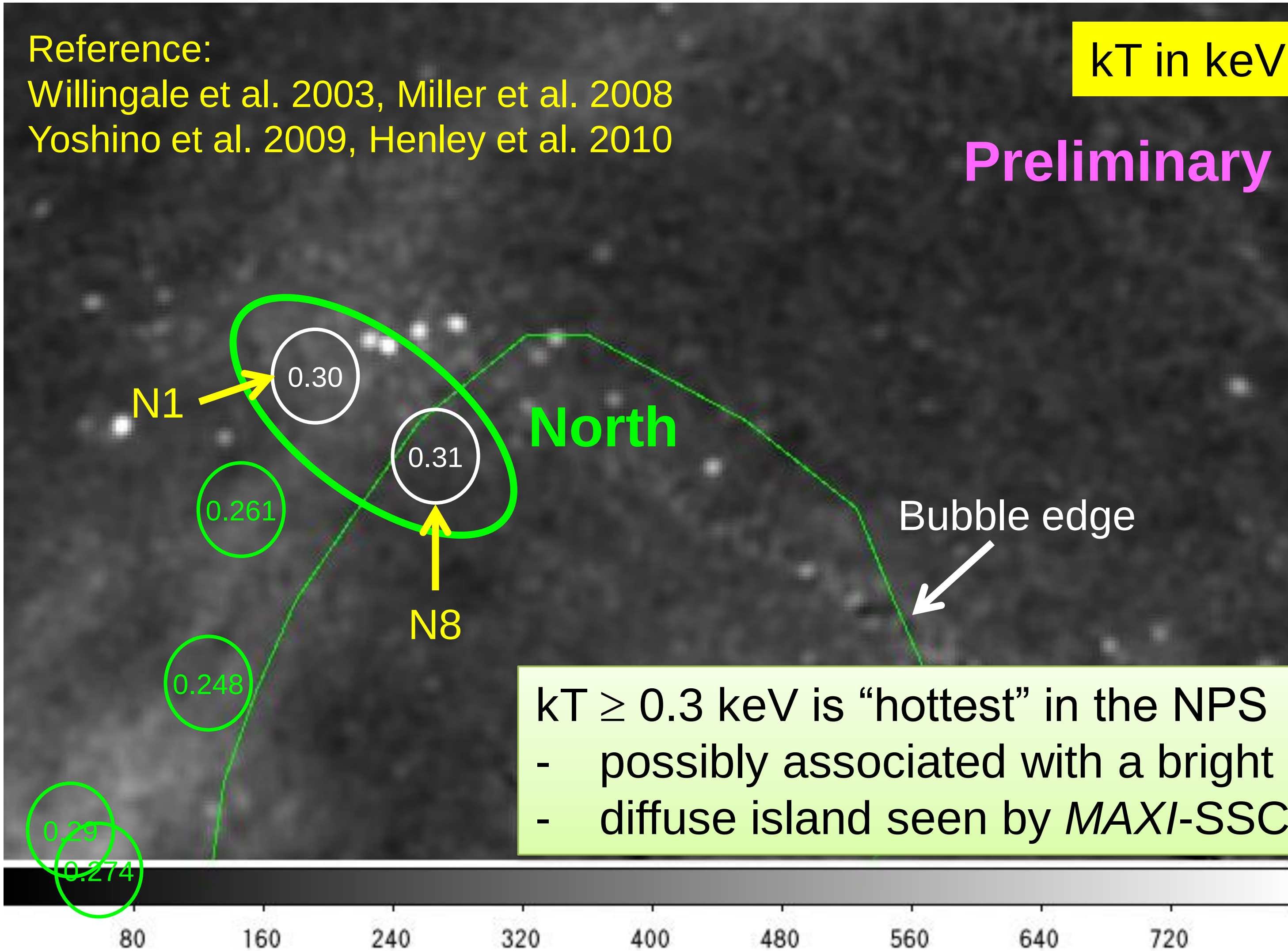


EM of the NPS in general is 10-100 times higher than GH average

kT distribution: all-sky

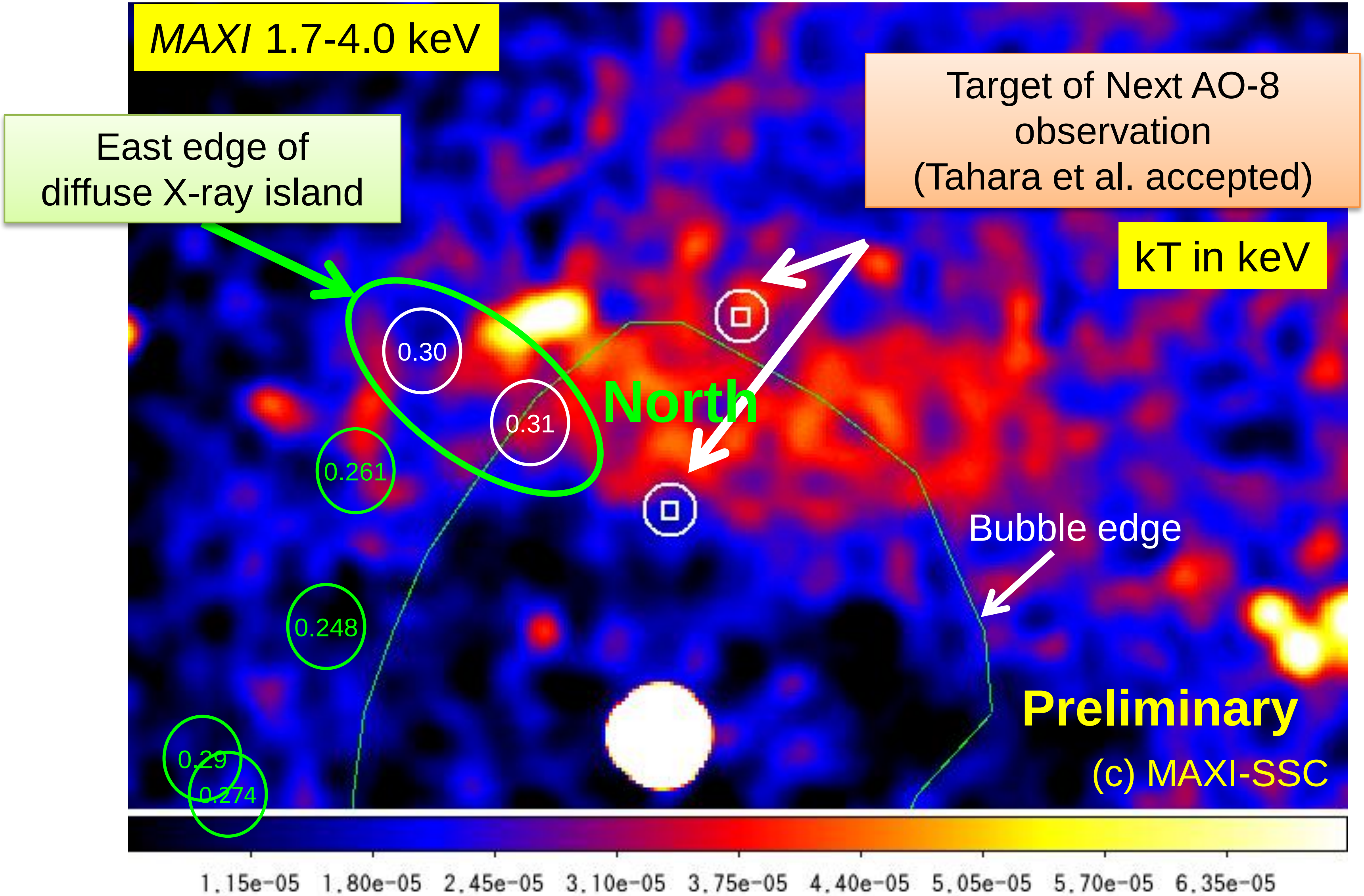


kT distribution near NPS edge

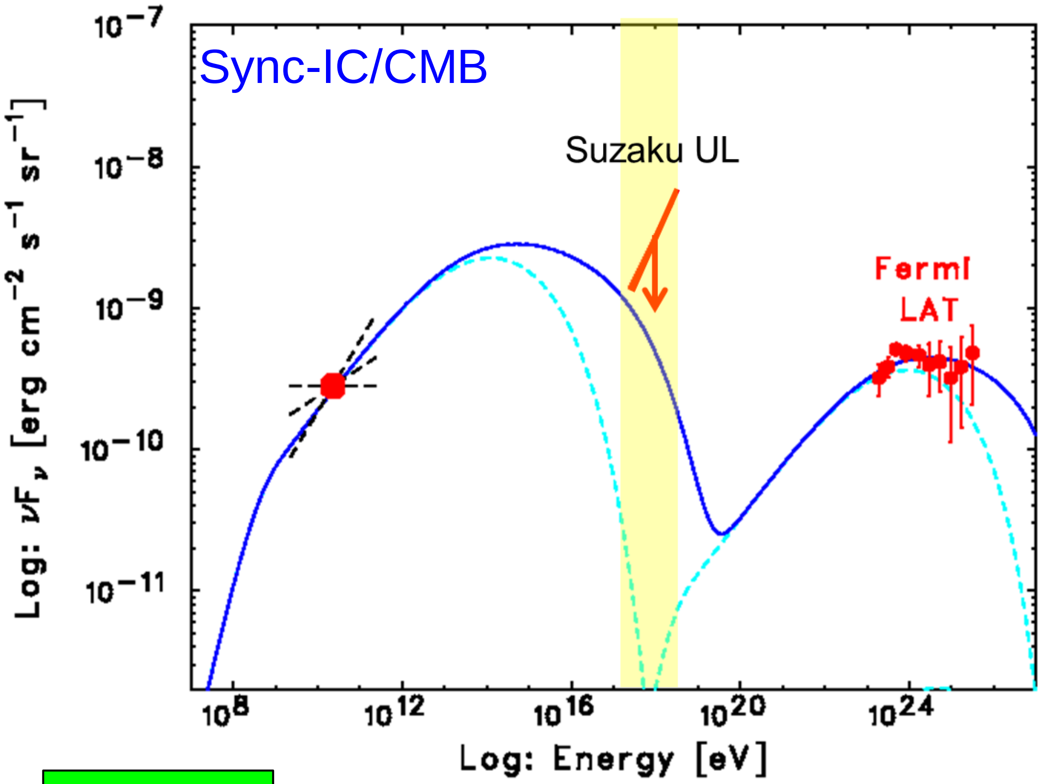


kT ≥ 0.3 keV is “hottest” in the NPS
- possibly associated with a bright
- diffuse island seen by *MAXI*-SSC

kT distribution on MAXI-SSC



Non-thermal vs Thermal Balance



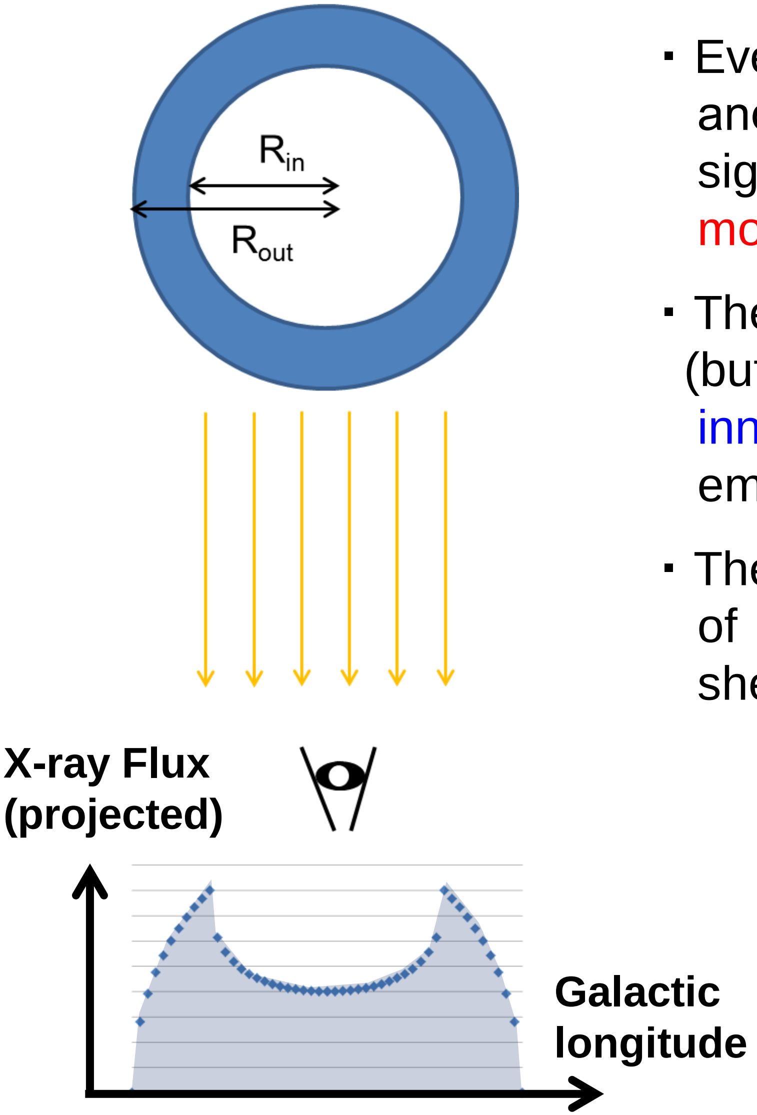
Non-thermal (SED model)

- B = 12 μG
  (U_B = 5.7x10^{-12} erg/cm^3)
- $U_{e,non\text{-}th}$ = 1.4 x10^{-12} erg/cm^3
- Spherical radius
  r = 1.2 x 10^{22} cm ~ 4 kpc
- $P_{non\text{-}th}$ ~ 1/3 x (U_e + U_B)
  ~ 2.0 x10^{-12} erg/cm^3
- $E_{non\text{-}th}$ ~ (U_e + U_B)x V
  ~ 10^{56} erg

Thermal

- P_{th} ~ n_e x kT = 2.5 x10^{-12} erg/cm^3
  (where we assumed n_e ~ 5x10^{-3} cm^{-3} , kT ~ 0.3 keV from NPS data)
- $E_{tot,th}$ ~ P_{th} x V ~ 10^{56} erg
  (where we assumed thickness of envelop is ~1/2 of bubble radius, ~2 kpc)

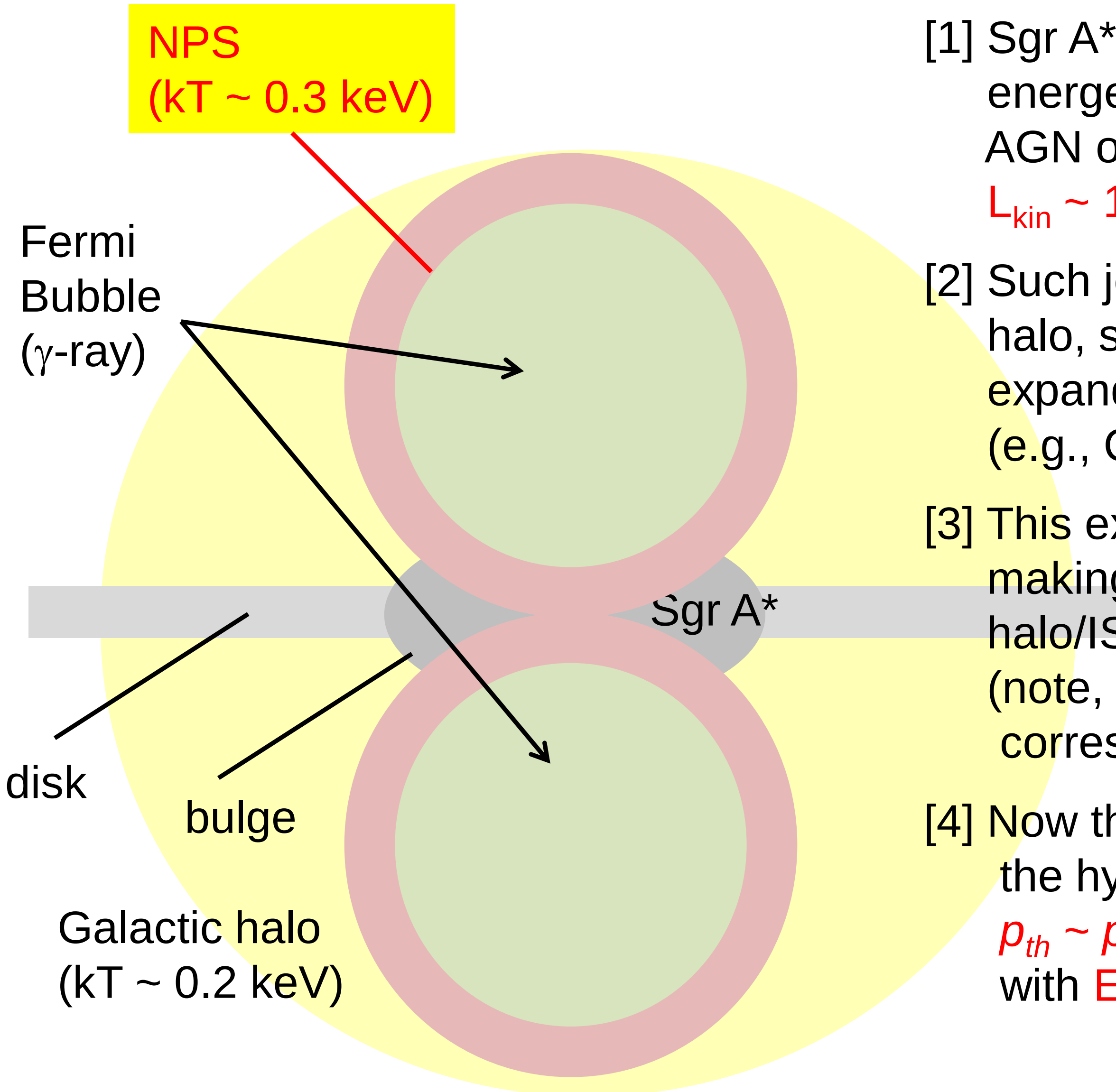
Why only EM varies, but constant kT ?



- Even if the bubble structure has a sharp edge and are symmetric w.r.t the observer's line of sight, what we could observe is a "projected" morphology onto the sky
- Therefore we expect to observe non-zero (but same kT) thermal emission even from the inner bubble, as an accumulation of the X-ray emission from the surface of the bubble
- The situation is quite similar to the scale width of SNR shell, a projection of (intrinsically) sheet-like structures with curved shape

A toy projection model assuming spherical geometry of the bubble, and $R_{in} : R_{out} = 3 : 5$ where $R_{in} = 4$kpc

Current Picture



[1] Sgr A* in the past may produce energetic outflow (jet or wind) like AGN or starburst galaxies, with $L_{kin} \sim 10^{42-43}$ erg/s

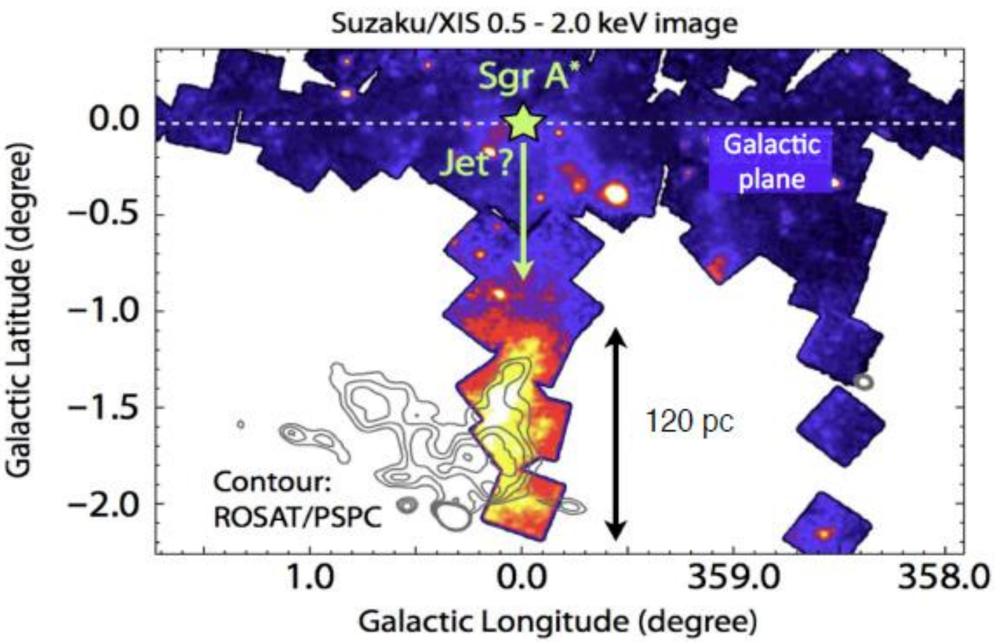
[2] Such jet makes baby bubbles in the halo, sweep up halo/ISM gas like expanding cocoon in the AGN (e.g., Cygnus A ; *Willson et al. 2002*)

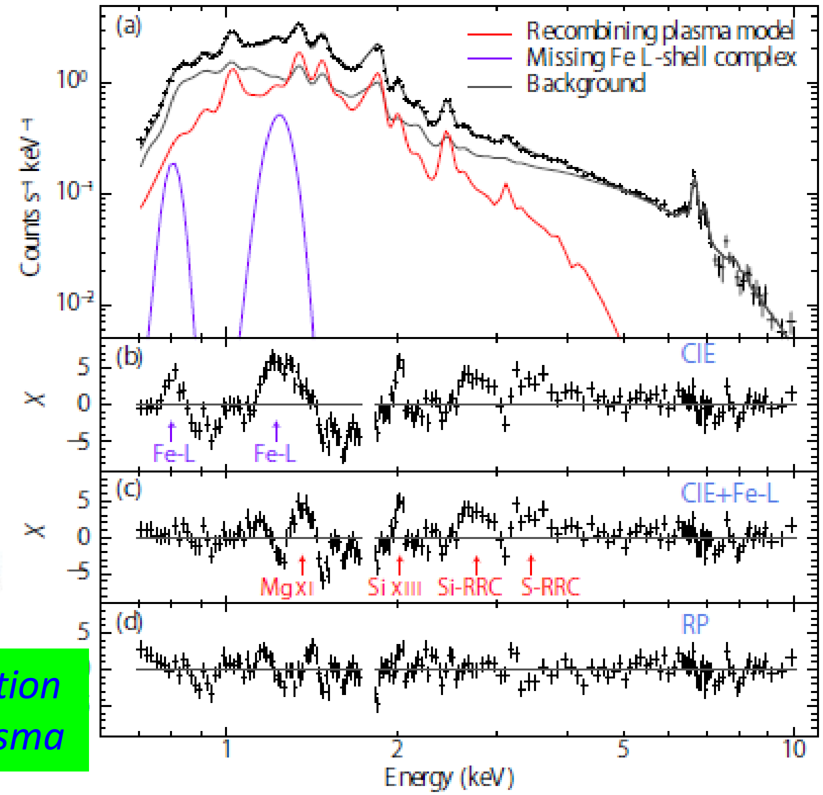
[3] This expansion is rather slow without making shock, since it heats up halo/ISM plasma only to 0.3 keV (note, $kT = 0.2 \rightarrow 0.3$ keV corresponds to only ~ 200 km/s!)

[4] Now the bubble and the NPS is in the hydrostatic equilibrium, with $p_{th} \sim p_{non\text{-}th} \sim 2\times10^{-12}$ erg/cm^3, with $E_{tot} \sim 10^{56}$ erg

Another Relic of GC Activity

Nakashima et al. 2013 in prep





CIE: collisional ionization
RP: recombining plasma

- Suzaku found an island of thermal emission of about 0.5 keV temperature at around *(l, b)= (0°, −1°.5)*
- Remarkable features of this plasma is that it has a jet-like structure ejected from Sgr A∗ and the plasma is in recombining process
- Almost fully ionized plasma was made by jet-like activity (flare) of Sgr A∗ about 2×10^5 years ago, and then now is still in recombining phase

Summary

I have reviewed most recent X-ray observations possibly related with the Fermi Bubble, and its interpretation

- Galactic Halo
  - Surprisingly uniform kT of 0.2 keV, but EM changes order of magnitude from (0.5 ~ 6) x10^{-3} cm^{-6} pc

- NPS and its edge
  - It is still debatable if the structure is nearby SNR or associated with GC
  - kT ~ 0.3 keV with EM ranges from (50 - 200) x10^{-3} cm^{-6} pc
  - EM changes 50 % at the edge of bubble, but kT remains constant

- Interpretation
  - Pressure balance and total energy stored in the bubble is consistent with a scenario that the NPS is in the hydrostatic equilibrium
  - Another evidence for recombining plasma found by Suzaku

More will come soon by Suzaku/MAXI!